From Tomography to Material Properties of Thermal Protection Systems

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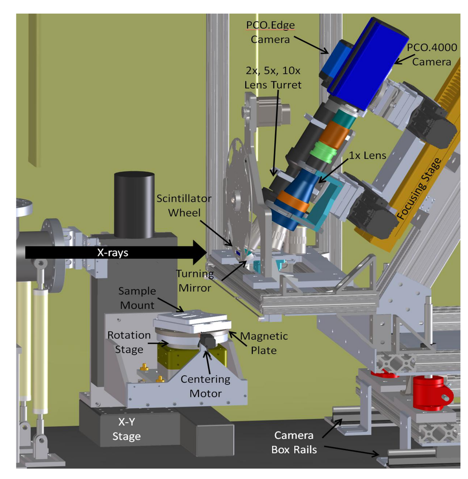
Overview of the Effort

A NASA Ames Research Center (ARC) effort, under the Entry Systems Modeling (ESM) project, aims at developing micro-tomography (micro-CT) experiments and simulations for studying materials used in hypersonic entry systems. X-ray micro-tomography allows for non-destructive 3D imaging of a materials micro-structure at the sub-micron scale, providing fiber-scale representations of porous thermal protection systems (TPS) materials. The technique has also allowed for In-situ experiments that can resolve response phenomena under realistic environmental conditions such as high temperature, mechanical loads, and oxidizing atmospheres. Simulation tools have been developed at the NASA Ames Research Center to determine material properties and material response from the high-fidelity tomographic representations of the porous materials with the goal of informing macroscopic TPS response models and guiding future TPS design.

Hard X-ray Micro-Tomography

Hard X-rays can penetrate dense materials enabling the imaging of sample interiors. A tomography scan is achieved by collecting radiographic images (typically 1025) over a 0-180 deg. rotation of the sample. The radiographs are converted into visible light by a single crystal scintillator. The visible light is imaged through magnification lenses onto a pixel detector. The ALS synchrotron provides X-ray energies in between 8 and 45 keV enabling spatial resolutions in the sub-microns range. Data set collection times can vary between ~10 sec to 1 hour. Advanced reconstruction algorithms and supercomputing are used for 3D image reconstruction and data processing.

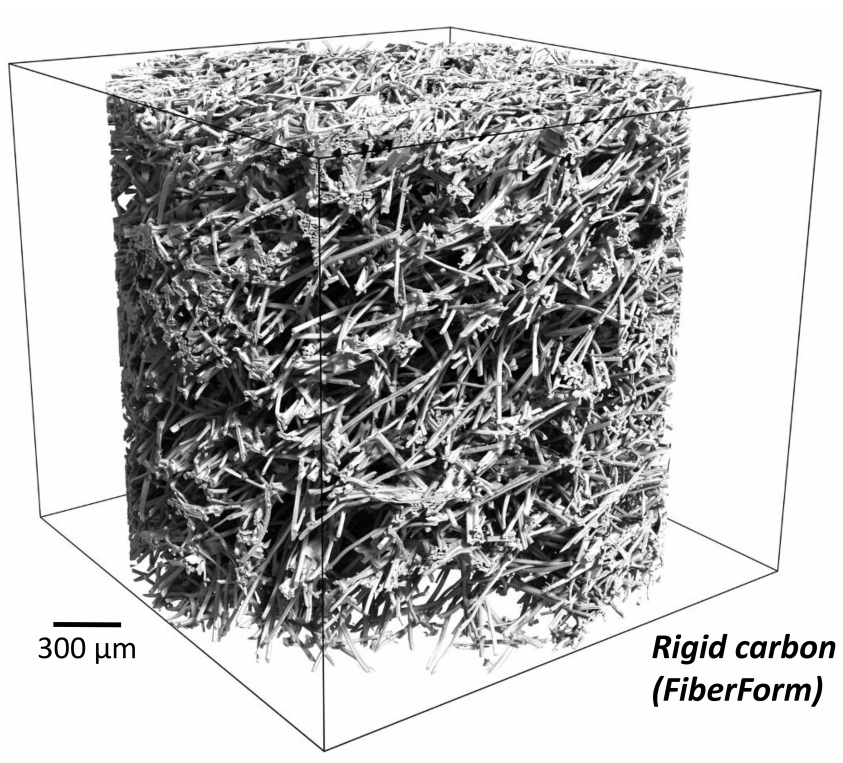


Schematic of the micro-CT setup at the Advanced Light Source

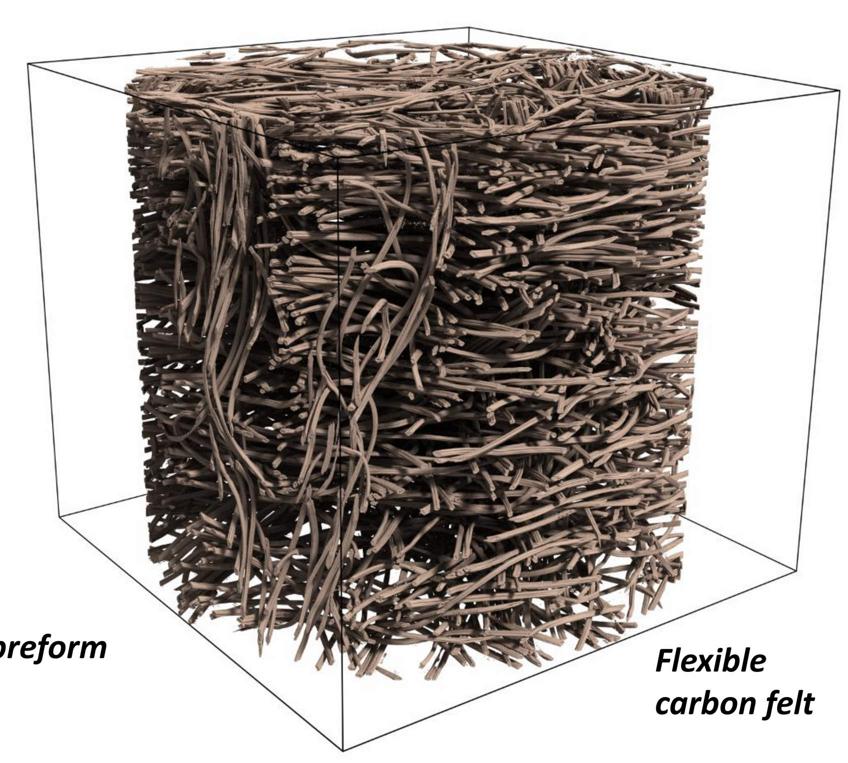
Micro-tomography of Ablative TPS Materials

A wide range of materials are imaged from the sub-micron to centimeter scale. The high quality tomography reveals 3D features of complex microstructures, woven architectures, and decomposition phenomena.

Fibrous Preforms for Lightweight Ablators



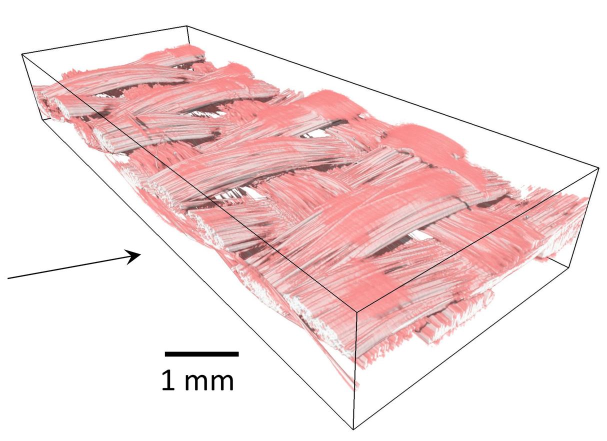
Rigid carbon preform (FiberForm)

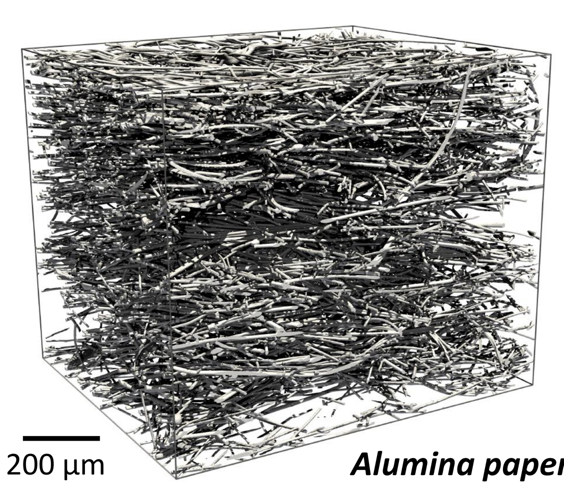


Flexible carbon felt

Flexible TPS Materials

Alumina-boria-silica fabric

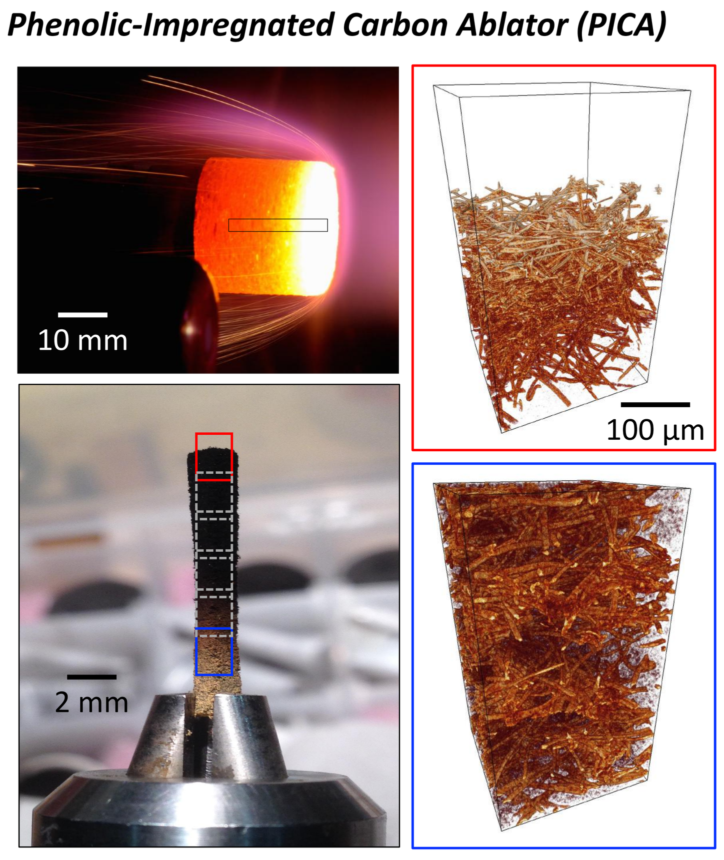




Alumina paper

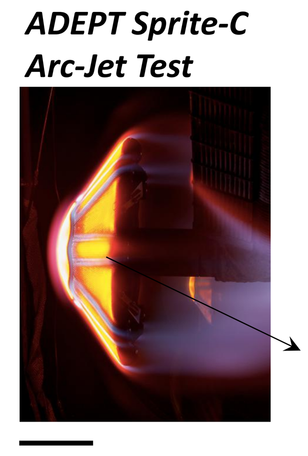
Post-test Characterizations of Arc-Jet Samples

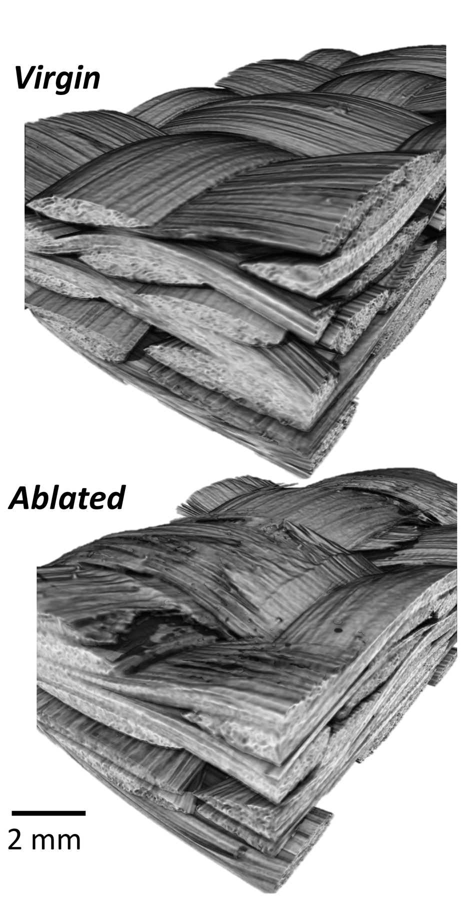
Phenolic-Impregnated Carbon Ablator (PICA)



3D woven carbon fabric

ADEPT Sprite-C Arc-Jet Test

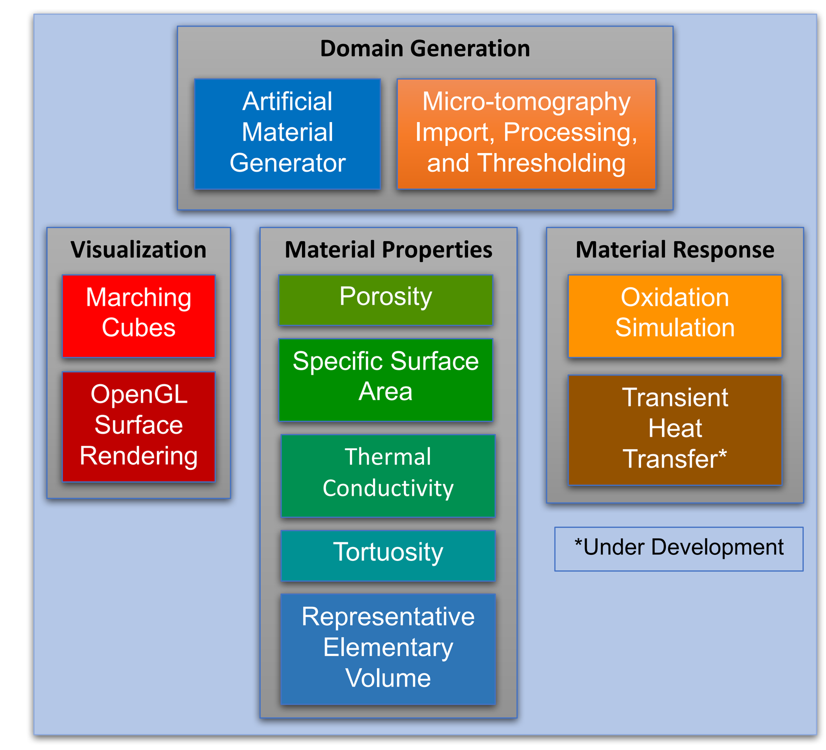




Micro-tomography based simulations

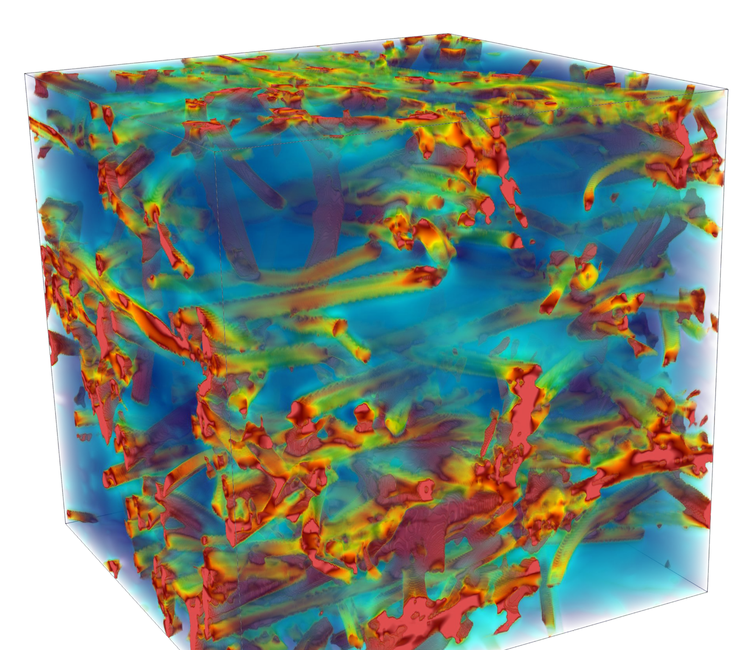
The Porous Materials Analysis (PuMA) software has been developed to determine a materials effective properties and response based on its micro-structure (either tomographic or computationally generated). The GUI-based PuMA platform allows tomography segmentation and 3D image rendering based on a marching cube discretization of the tomography iso-surfaces.

Architecture of PuMA v. 2.1

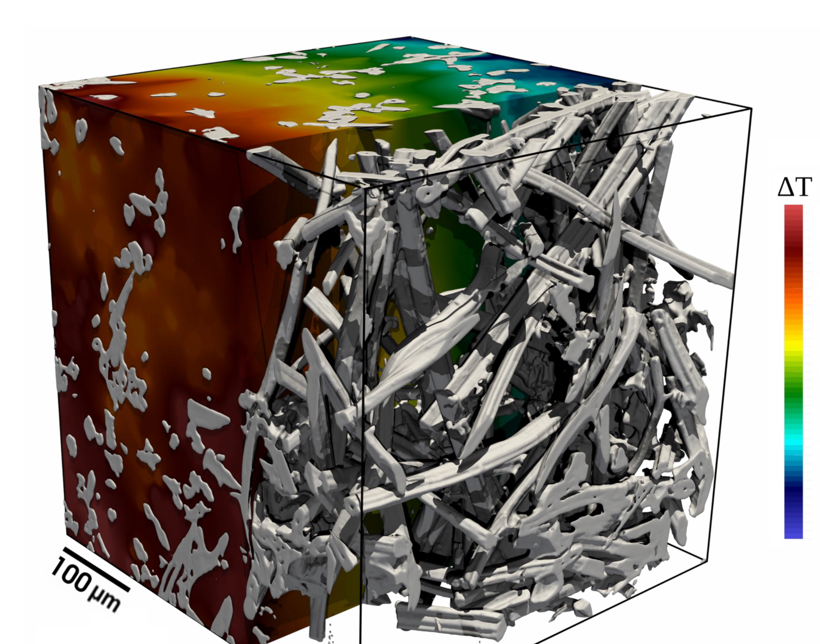


Effective Material Properties

Simulation tools have been developed to compute the porosity, specific surface area, thermal conductivity, electrical conductivity, diffusivity, tortuosity, and representative elementary volume of a material based on its micro-structure[1].



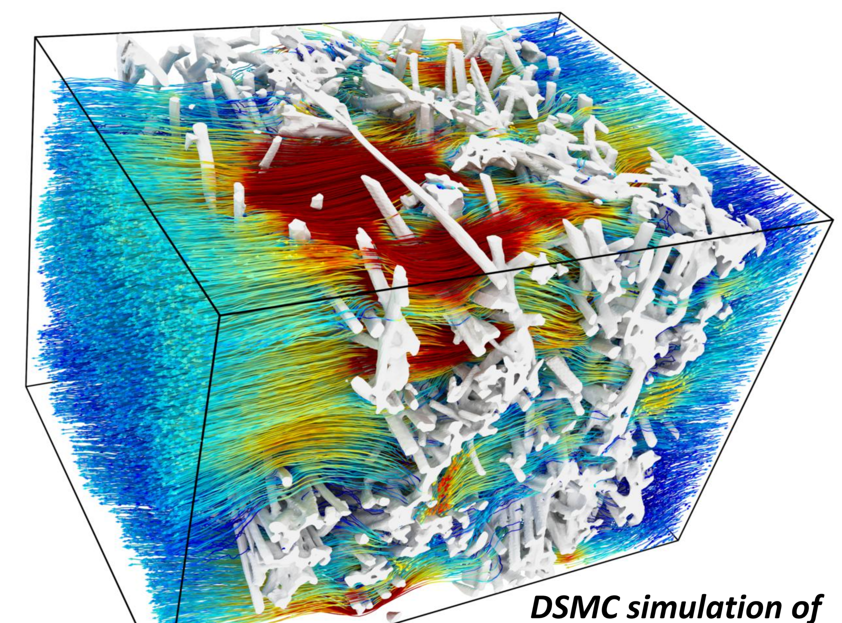
Steady state current flow through carbon fiber preform



Steady state temperature in carbon fiber preform

Permeability using DSMC

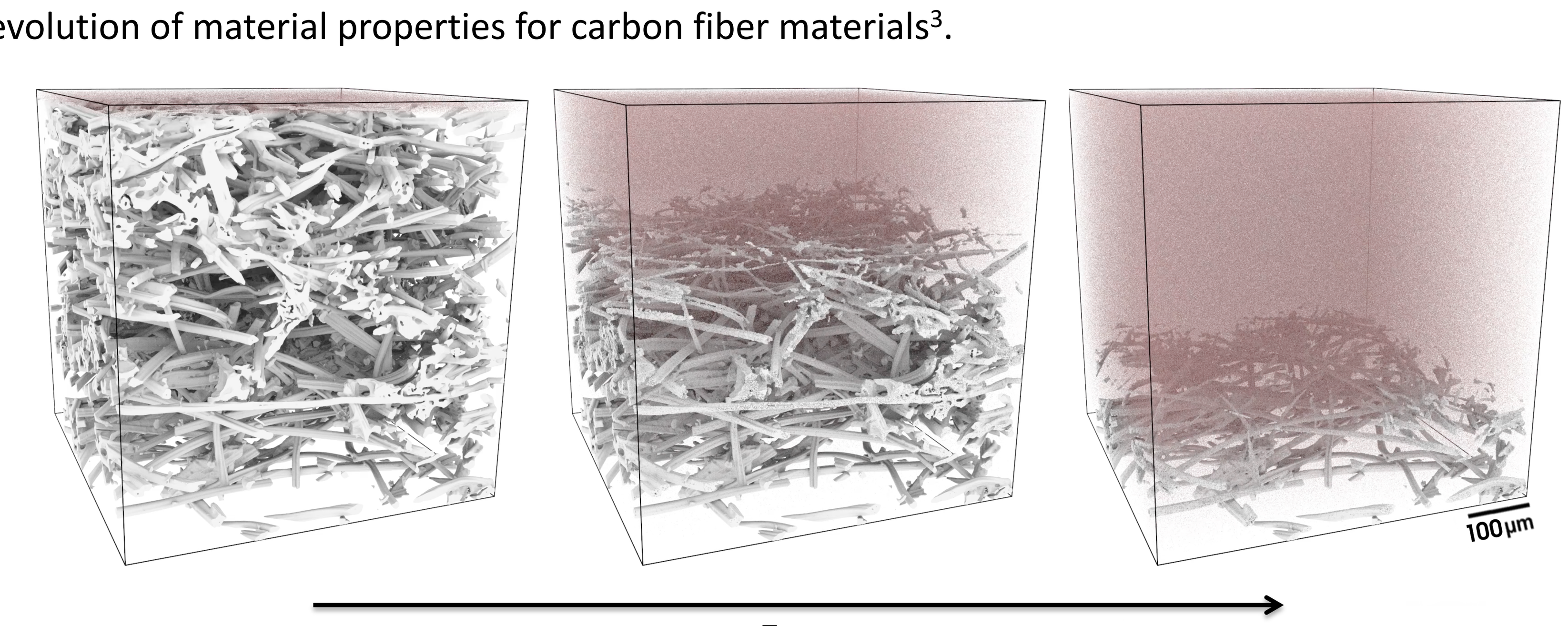
Direct Simulation Monte Carlo (DSMC) methods enable the simulation of fluid flow in the rarified regime, where typical CFD methods are no longer valid. Using the SPARTA software, developed at Sandia National Labs, we can determine the permeability[2] of a material based on its tomographic microstructure for all Knudsen numbers.



DSMC simulation of gas flow through a carbon fiber material

Micro-scale Oxidation Simulations

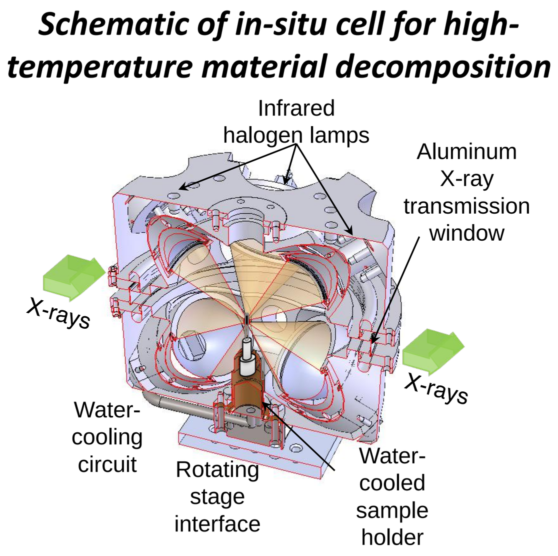
Microscale oxidation phenomena are simulated using a random walk model for reactant diffusion and a sticking probability law for surface reactions. Using the simulation tool PuMA, we can study the decomposition behavior at different diffusion/reaction regimes, and quantify the resulting evolution of material properties for carbon fiber materials[3].



In-situ Micro-tomography of Heat Shield Materials Decomposition

In-situ sample cells are designed to mimic material use conditions. For fibrous carbon substrates a 6-poles lamp-heated furnace has been adapted to host micro-plug samples exposed to a controlled flow oxidizing gas.

Schematic of in-situ cell for high-temperature material decomposition



Progressive micro-scale oxidation decomposition of FiberForm under air at 900 K

References

1. F. Panerai, J. C. Ferguson, J. Lachaud, A. Martin, M. J. Gasch, N. N. Mansour, Micro-tomography based analysis of thermal conductivity, diffusivity and oxidation behavior of rigid and flexible fibrous insulators, International Journal of Heat and Mass Transfer 108 (2017) 801–811.
2. A. Borner, F. Panerai, N.N. Mansour, High temperature permeability of fibrous materials using direct simulation Monte Carlo, Int. J. Heat Mass Transf. 106 (2017) 1318–1326
3. Ferguson J, Panerai F, Lachaud J, Martin A, Bailey SCC, Mansour NN. Modeling the oxidation of low-density carbon fiber material based on micro-tomography. *Carbon* 96 (2016) 57-65.

Acknowledgments

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